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Effects of Aggregate Structure on Hot-Mix Asphalt Rutting Performance in Low Traffic Volume Local Pavements

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Abstract

The objective of this study is to evaluate the effect of mix gradations associated with the Superpave restricted zone on rutting potential specifically for low traffic volume roadways. Although the elimination of the restricted zone requirement in Superpave mix design is highly recommended, some questions still remain unanswered as the research conclusions supporting the elimination of the restricted zone were largely made for medium to high traffic volume roadways, where aggregates are highly crushed and of good quality. The applicability of such research conclusions based on high traffic volume mixes needs to be verified for low volume mixes because many states in the United States (US) use noncrushed local aggregates for low traffic volume pavements, which might be related with aggregate gradation. This paper summarizes the research findings obtained from a systematic approach consisting of (1) statistical analyses of preexisting data accumulated for quality assurance purposes, (2) experimental investigations based on the statistical analysis results, and (3) in-field investigation of the rutting performance of low traffic volume pavement. The comparison and analysis results indicate that similar to that for medium to high traffic volume pavements, the restricted zone is not a controlling factor affecting hot-mix asphalt rutting performance for low traffic volume local pavements. The fineness of aggregate gradation rather than the restricted zone seems to be a factor that affects rutting performance.

Keywords: Superpave, restricted zone, rutting performance, low traffic volume pavement

1. Introduction

The Superpave system was developed on the basis of data largely obtained from medium to high traffic volume roadways. Therefore, it has been primarily used on medium to high traffic volume roadways with great success, while the majority of pavement networks in many states, including Nebraska, experiences only low traffic volumes. Due to the significant number of pavement networks that are subjected to only low traffic volumes, an effective implementation of the Superpave technique for low traffic volume pavements has been an issue of growing interest. Moreover, the limitations on the availability and the quality of local materials (particularly aggregates) and the issues of local economy have brought greater attention on the implementation of appropriate designs and performance evaluation for the low traffic volume roadways. Recently, several studies [1–5] have been conducted to investigate the suitability of the Superpave system, (in particular, the mix design concepts) as compared to traditional methods for low traffic volume roadways. A proper implementation of the Superpave system for low traffic volume roadways will allow state highway agencies to employ a single specification system. It enables agencies to control the construction and management of roadway systems in a simpler and more unified manner while at the same time improving the pavement performance.

The state of Nebraska has implemented the Superpave system in all flexible pavement projects since 1999. A total of eleven mix types (named *SPS*, *SPL*, *SP-1* to *SP-6*, *SP0-4 Special*, *RLC*, and *LC*) are currently implemented in Nebraska, but only three mixes (i.e., *SP-4 Special*, *SP-4*, and *SP-5*) are primarily used for low (less than 1 million equivalent single axle loads (ESALs)), medium (1–10 million ESALs), and high (more than 10 million ESALs) traffic volume roadways, respectively. Table 1 presents the required aggregate properties and volumetric characteristics of these three mixes plus another mix type, *SP-2*. The *SP-2* mix was used for the hot-mix asphalt (HMA) surface layers for low traffic volume roadways until 2003. After 2003, the *SP-4 Special* mix replaced the *SP-2* mix.

Table 1. Required aggregate properties and volumetric characteristics of each mix

Mix parameters	Mix type			
Aggregate properties	*SP-2*	*SP-4 Special*	*SP-4*	*SP-5*
Coarse aggregate angularity (minimum)	65	85/80	85/80	95/90
Fine aggregate angularity (minimum)	43	45	45	45
Sand equivalency (minimum)	40	45	45	45
lat and elongated (maximum)	10	10	10	10
Volumetric characteristics				
% Air voids	3–5	3–5	3–5	3–5
% Voids in mineral aggregate (minimum)	14	14	14	14
% Voids filled with asphalt	65–78	65–75	65–75	65–75
Dust/binder ratio	0.7–1.7	0.7–1.7	0.7–1.7	0.7–1.7
% Reclaimed asphalt (maximum)	25	25	15	15
No. of gyrations (at N_{max})	117	117	152	174

In the process of implementing the Superpave system for low traffic volume local roadways, greater attention should be paid to the aggregate characteristics than the binder properties. It is due to the well-known fact that the study of aggregates and their impact on pavement behavior was not sufficiently established compared with the binder aspects when the Superpave system was initiated in the US. One of the recommendations initially made regarding aggregates was the use of a restricted zone (RZ) that forms a band through which gradations were recommended not to pass, since the mixtures passing through the RZ are believed to be rut-susceptible. However, the RZ concept remained questionable due to a lack of scientific rigor applied to its verification, which consequently resulted in numerous studies [6–14]. Including a major effort through the National Cooperative Highway Research Program (NCHRP) project [10], most studies have generally concluded that the RZ is a redundant requirement. One of general findings of these studies is that fine-graded (above-RZ and through-RZ) mixtures usually provided better performance than coarse-graded (below-RZ) mixtures. Technically, adequate HMA performance could always be obtained with gradations ranging from above-RZ to below-RZ, indicating that there was no significant relationship between the Superpave RZ and the HMA rutting or fatigue performance.

The elimination of the RZ requirement in the Superpave mix design is highly recommended today. However, some questions still remain as the research conclusions supporting the elimination of the RZ criteria were largely made for medium to high traffic volume roadways where the coarse aggregate angularity (CAA) of aggregates is close to 100 (inferring 100% crushed coarse aggregates). The applicability of such research conclusions to low traffic volume local mixes in many states, including Nebraska, needs to be verified because a majority of the aggregates used for low traffic volume local mixes are generally low-quality, inexpensive, and noncrushed. The local aggregates rarely close to a CAA of 100 but typically between 65 and 85. Based on this motivation, the Nebraska Department of Roads (NDOR) has initiated a research project to better understand the effect of the aggregate structure on the rutting performance of low traffic volume local pavements. This paper summarizes the findings obtained from a systematic research approach consisting of (1) statistical analyses of pre-existing data accumulated by the NDOR for quality assurance purposes, (2) experimental investigations performed based on the statistical analysis results, and (3) in-field investigation of the rutting performance of low traffic volume pavements.

2. Statistical investigation

To evaluate the effects of the aggregate structure on the rutting performance of low traffic volume local pavements, *SP-2* and *SP-4 Special* mix data accumulated by the NDOR were obtained and statistical analyses were performed. The NDOR has evaluated the HMA mixtures of each pavement construction project and recorded all the required materials/mixture properties and asphalt pavement analyzer (APA) test results for quality assurance purposes. The APA has been widely used in many states as a practical method to evaluate the HMA rutting potential in mix design and in applications involving quality control/quality assurance (QC/QA). A total of 39 samples of *SP-2* and 51 samples of *SP-4 Special* mix were found for this study. Table 2 presents the number of samples categorized by aggregate gradation (above-, through-, and below-RZ) and their mean, standard deviation, minimum, and maximum of APA rut rate of each mixture. The rut rate can be defined as the rut depth per APA loading cycle and simply calculated by dividing the total rut depth by the corresponding number of loading cycles. It was used herein instead of the total rut depth at 8000 cycles to equivalently compare rutting potential of each mixture. This is because the APA test automatically stopped when the wheel loading reached 8000 cycles before a 12-mm rut depth or when the total rut depth exceeded 12 mm. To provide an identical measure of the mixture rut potential for any case, the rut rate was calculated and used, even though its quantity is small as shown in table 2. By simply looking at the mean rut rate of each gradation type in table 2, it can be generally concluded that the above-RZ mixture is more rut resistant than the other mixtures, and the below-RZ mixture is the most prone to rutting.

Table 2. Rut data statistics for *SP-2* and *SP-4 Special* mixes with different gradations

Gradation type	No. of samples	Mean	Standard deviation	Minimum	Maximum
SP-2 mix					
Above-RZ	8	0.003307	0.001702	0.001233	0.006416
Through-RZ	19	0.011606	0.008236	0.000722	0.028870
Below-RZ	12	0.015321	0.018714	0.000528	0.048624
SP-4 Special mix					
Above-RZ	12	0.000508	0.000219	0.000229	0.000855
Through-RZ	30	0.002616	0.002306	0.000430	0.008115
Below-RZ	9	0.003115	0.001934	0.000979	0.007170

Even if table 2 can provide a performance rank order of gradation types based on their mean rut rate, the performance ranking should be estimated with more care since the performance differences among gradation types may not be statistically significant; in other words, the rank order simply determined based on the mean rut rate shown in table 2 may not be true because of variances in the rut rate data among mixtures. For a better understanding, statistical comparisons were performed utilizing the analysis of variance (ANOVA) technique. ANOVA is a simple and well-known technique that can be used to determine the impact of gradation types corresponding to the restricted zone on the rutting potential of mixtures. Table 3 presents the results of ANOVA. On the basis of the *F*-statistics and the *P*-value, the gradation is a significant factor affecting the APA rut depth with a 90% significance level ($\alpha = 0.10$) for the *SP-2* mix and a 99% significance level ($\alpha = 0.01$) for the *SP-4 Special* mix, which implies that the mean rut rates are not statistically equal but are influenced by the aggregate gradation with regard to the restricted zone.

Table 3. ANOVA results for rut rate of each mixture

Source of variation	Degree of freedom	Sum of squares	Mean square	*F*-statistics	*P*-value
SP-2 mix					
Gradation	2	0.0007043	0.0003522	2.49	0.097
Error	36	0.0050936	0.0001415		
Total	38	0.0057979			
SP-4 special mix					
Gradation	2	0.0000471	0.0000235	6.12	0.0043
Error	48	0.0001847	0.0000039		
Total	50	0.0002318			

In an attempt to further investigate the significance of gradation identified by ANOVA, a contrast analysis between the levels (i.e., above-, through-, and below-RZ) of the factor (i.e., aggregate gradation) was conducted to assess the significance of these individual comparisons. In table 4, the contrast sums of squares are calculated, and the significance of these comparisons are presented by the *F*-statistics and the *P*-value for each contrast. It can be observed from the table that the 90% significance level (*P*-value of 0.097 in table 3) from the *SP-2* data was primarily due to the significance between the above-RZ and through-RZ mixtures (*P*-value of 0.033 in table 4), and the 99% significance level (*P*-value of 0.0043 in table 3) obtained from the *SP-4 Special* was from performance contrasts between the above-RZ and through-RZ (*P*-value of 0.004 in table 4) mixtures and between the above-RZ and below-RZ mixtures (*P*-value of 0.003 in table 4). There was no significant contrast observed between the below-RZ and the through-RZ mixtures from both the *SP-2* and the *SP-4 Special* mixes. This indicates that the mixture violating the Superpave RZ concept (i.e., through-RZ mixture) does not necessarily have a higher rut potential in low traffic volume local roadways compared with the gradations satisfying the Superpave RZ limitation, such as the below-RZ mixture.

Table 4. Contrast analysis results

Contrast	Degree of freedom	Contrast sum of squares	*F*-statistics	*P*-value
SP-2 mix				
Above vs. through	1	0.0006928	4.90	0.033
Through vs. below	1	0.0001015	0.72	0.403
Above vs. below	1	0.0003877	2.74	0.107
SP-4 Special mix				
Above vs. through	1	0.0000350	9.08	0.004
Through vs. below	1	0.0000017	0.45	0.507
Above vs. below	1	0.0000381	9.90	0.003

3. Laboratory experimental investigation

Based on preliminary findings from the statistical analyses using the accumulated NDOR data, two experimental attempts were made in this study. First, the construction densification index (CDI) and the traffic densification index (TDI) concepts proposed by Mahmoud and Bahia [15] were used to characterize the constructability and rutting potential of each mixture. The CDI–TDI concept seems to be attractive because it is very simple to use and can be directly obtained from the volumetric mix design results. At the same time, it is based on rigorous scientific concepts to predict the constructability and rutting potential of mixtures by representing their densification characteristics using a Superpave gyratory compactor (SGC). Second, APA testing of HMA specimens designed with different aggregate gradations was performed for a more direct rutting performance estimation. The APA test results were then compared with the statistical analysis results and the CDI–TDI analysis results.

3.1. Materials

A total of six local aggregates (three limestone-based aggregates: 16-mm limestone, 6.4-mm limestone, and screenings; and three gravels: 2A, 3ACR, and 47B) that have been most widely used for low traffic volume pavements in Nebraska were selected and proportioned to meet the target properties of combined aggregate blends for the *SP-2* mix shown in table 1. Each aggregate blend was then moistened with three percent water by the total weight of the aggregates and mixed with one percent hydrated lime by the total weight of the aggregates. Hydrated lime is required for all Nebraska Superpave mixes to mitigate the moisture-related damage. After oven-drying the lime-aggregate blend, a Superpave performance-graded binder PG 64-22 was mixed with the lime-aggregate blend.

3.2. Mix design results

In order to simulate the HMA mixtures for low traffic volume pavements, a total of four mixtures (i.e., one above-, two through-, and one below-RZ) were designed. The resulting four mixture gradations are shown in figure 1. As presented, the gradations are similar except near the RZ. All four gradations follow the same trend from the 12.5-mm sieve down to the 4.75-mm sieve—no difference in the coarse aggregate part among the mixtures. From the 4.75-mm sieve, the above-RZ gradation passes above the RZ and below the upper control points. As shown in the figure, two crossover through-RZ gradations were utilized in this study. The first through-RZ is closer to the above-RZ gradation (indicating a finer mix), and the second through-RZ is closer to the below-RZ mix (indicating a coarser mix). By comparing the two different through-RZ mixtures, the influence of the mix coarseness (or fineness) on the rutting performance can be determined, if any significant effects appear. The remaining mixture is located below the RZ and above the lower control points.

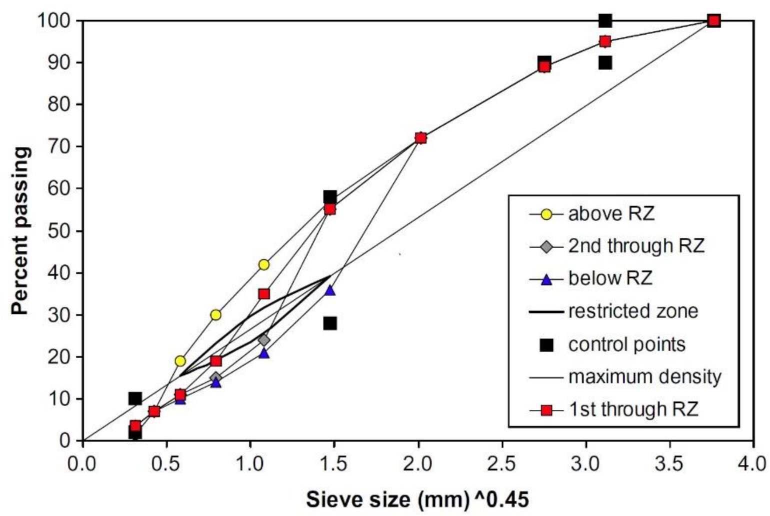

Figure 1. Gradation curves of all four mixtures.

In an attempt to better estimate the gradation effects regarding the restricted zone, the other aggregate properties in each mixture, such as angularity, specific gravity, and mineralogy; were controlled so as to produce mixtures that were as similar as possible, except in the aggregate structure. Table 5 presents the finally determined volumetric parameters and aggregate properties for each mixture. As can be seen in the table, the mixture volumetric characteristics and overall aggregate properties meet the NDOR *SP-2* mix specifications.

Table 5. Aggregate properties and volumetric properties of each mixture designed

Mix parameters	Specification requirement	Each mixture designed			
		ARZ[1]	1st TRZ[2]	2nd TRZ	BRZ[3]
Aggregate properties					
Bulk specific gravity	N/A	2.583	2.582	2.582	2.575
Coarse aggregate angularity minimum	65	84.6	84.6	84.6	84.6
Fine aggregate angularity minimum	43	42.90	42.95	42.89	42.93
Sand equivalency minimum	40	73	73	73	81
Flat and elongated maximum	10	1.0	0.0	0.0	0.0
Volumetric characteristics					
Bulk specific gravity	N/A	2.336	2.312	2.339	2.331
Maximum specific gravity	N/A	2.447	2.421	2.443	2.429
% Air voids	3–5	4.6	4.5	4.2	4.0
% Voids in mineral aggregate minimum	14	14.4	15.5	14.2	14.3
% Voids filled with asphalt	65–78	68.4	71.0	70.2	71.7
% Asphalt binder	N/A	5.36	5.65	5.29	5.27
Dust/Binder ratio	0.7–1.7	1.56	1.19	1.46	1.31

ARZ[1]: above restricted zone
TRZ[2]: through restricted zone
BRZ[3]: below restricted zone

3.3. Analysis of SGC densification characteristics

The primary use of the densification curve (%G_{mm} vs. the number of gyrations) produced by the SGC is to determine volumetric properties of Superpave mixes; however, the SGC densification curve can also be used to quantify the constructability and rutting potential of mixes. As schematically illustrated in figure 2, the CDI is the value of the area under the densification curve from the density at 8 gyrations to a density of 92% G_{mm}, which represents the work done during the construction period to achieve 8% air voids. The TDI can be calculated from the area under the densification curve from 92% density to 98% density, which represents the work required to resist traffic loading during the pavement's service life. Therefore, mixtures with lower values of CDI have better constructability, while too low CDI can be an indication of a tender mixture and should be avoided. Mixtures with higher TDI values are typically desirable because they are expected to take more traffic during their lifespan due to better stability with less rutting potential. The CDI-TDI concept has been recommended as an initial screening criterion to select mixture for various traffic levels, in addition to indicating the expected performance levels.

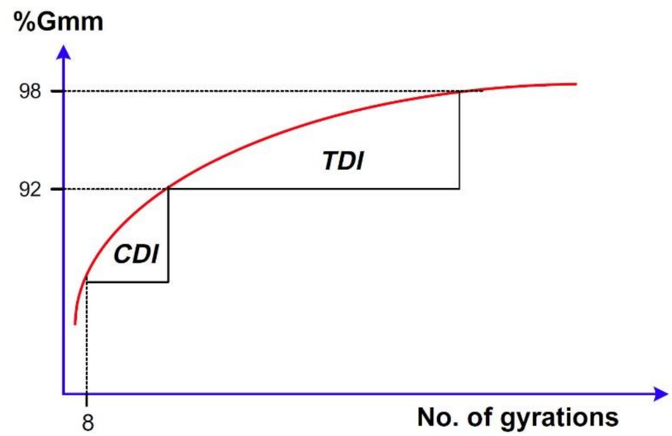

Figure 2. Illustration of the CDI–TDI concept.

Average values of the CDI and TDI obtained from each gradation category (above-RZ, through-RZ, and below-RZ) in this study are presented in figure 3. As discussed earlier, lower values of CDI and higher values of TDI are generally desirable, and from the figures, it can be seen that the above-RZ mixture is most likely to have the best performance, while the below-RZ mixture is more susceptible to rutting than the other mixtures. The trends shown in these figures agree well with the conclusions drawn from many other RZ-related studies that were performed typically for medium to high traffic volume Superpave mixes. The performance ranking presented in figure 3 is also consistent with the findings from the statistical analyses using the NDOR *SP-2* and *SP-4 Special* mix data.

3.4. APA performance testing and results

APA testing was performed to evaluate the rutting performance of each mixture depending on the aggregate gradation (RZ-associated). APA testing was selected in this study because it can be directly correlated with the findings from the statistical analyses, which also involve APA measurements, and the testing is relatively simple to perform and directly affords the rutting potential of mixtures by simply measuring the sample rut depth. APA tests were conducted at 64°C on dry SGC-compacted HMA cylinders that were 75-mm high with 4.0 ± 0.5% air voids to 8000 cycles. If the APA specimen demonstrated rut depth greater than 12 mm before the completion of the 8000 cycles, the testing was stopped and the corresponding number of strokes at the 12-mm rut depth was recorded.

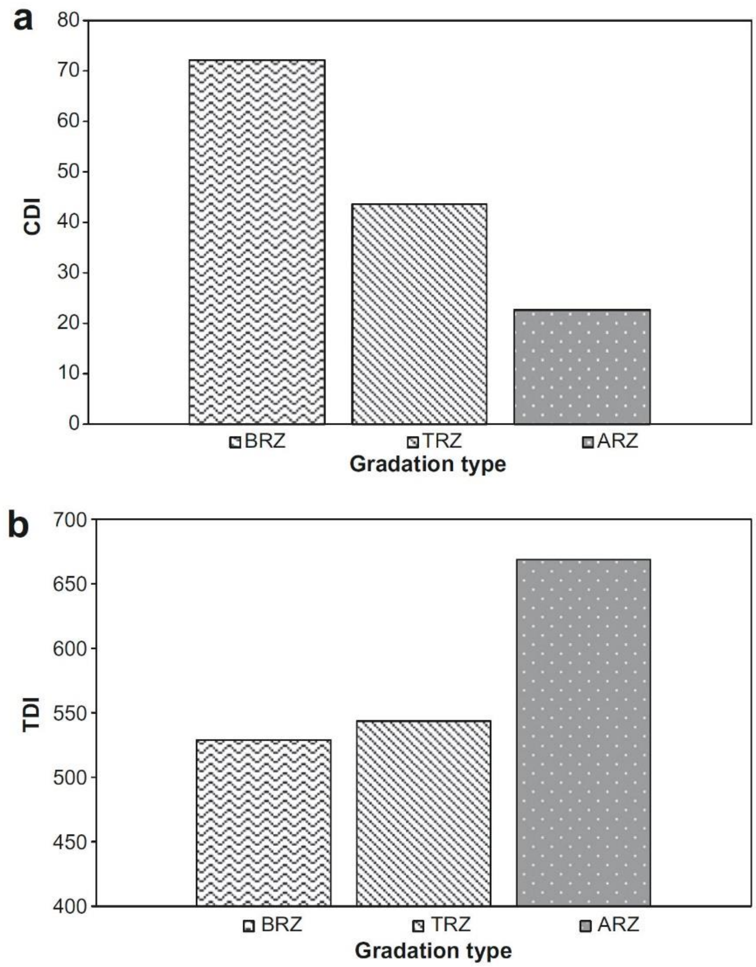

Figure 3. Construction densification index (CDI) and traffic densification index (TDI) of each mixture.

Table 6 presents a summary of the APA performance testing results for all four mixtures. Considering all the data, the above-RZ and through-RZ mixtures generally performed well, and the below-RZ mixtures demonstrated greater susceptibility to rutting. Another fact to be noted from the table is that the first through-RZ mixture, which was closer to above-RZ mixture gradation (indicating finer-graded mixture), was more rut-resistant than the second through-RZ mixture, which was closer to the below-RZ gradation (indicating a coarser-graded mixture). As noted, a better rut-resisting potential for above-RZ mixtures and/or finer-graded mixtures as compared to coarser-graded mixtures has also been reported in many other studies [7–9,16].

Table 6. APA test results

Mixture	Set no.	Number of cycles	APA rut depth (mm)
Above-RZ	1	8000	5
	2	8000	5.6
1st Through-RZ	1	8000	4.2
	2	8000	6.6
2nd Through-RZ	1	8000	7.5
	2	5300	9.1
Below-RZ	1	6000	10.4
	2	6390	11.9

In an attempt to compare the APA rut behavior of all the tested mixtures in a better manner, the rut rate—defined earlier as the rut depth per APA cycle—was calculated; subsequently, a bar chart presenting the rut rate of each mixture was constructed, as illustrated in figure 4. Figure 4 indicates that as long as the aggregate and mixture met other Superpave requirements, the HMA aggregate gradations going through the RZ performed similar to or better than mixtures with gradations entirely outside the RZ.

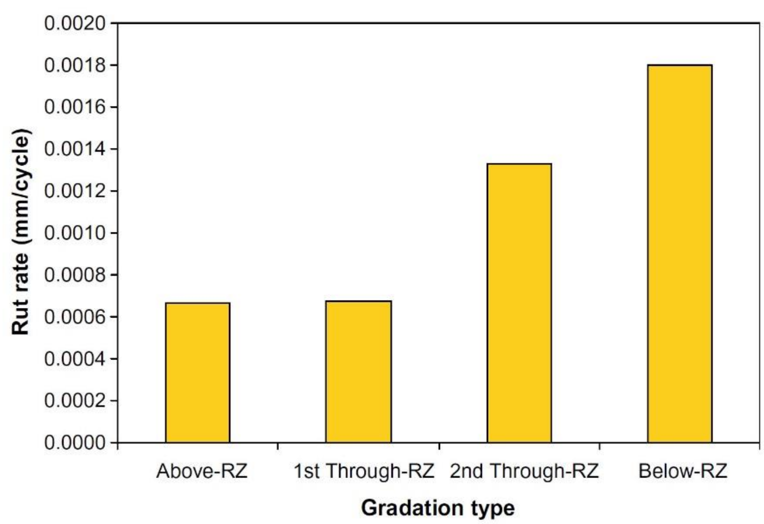

Figure 4. Rut rate of each mixture.

4. Field investigation

In addition to the statistical analyses using the NDOR data and the experimental investigations through the CDI-TDI concept and the APA performance test, in-field performance observations were also made to explore the effect of the RZ on the rut depth in low traffic volume local pavements in Nebraska. For better comparisons, pavement projects completed at the same time (in 2004) with the same mix type (SP-4 Special) were considered, and as shown in table 7 and figure 5, a total of eleven projects (three projects above-RZ, six projects through-RZ, and two projects below-RZ) were found. Only a limited number of projects could be taken into account for this field investigation due to limitations in the field data available.

Table 7. A list of highways in Nebraska selected for field investigation

No.	Location	Highway No.	Length (km)	Gradation
1	South of Culbertson	17	28.40	Through-RZ
2	Pleasanton-Hazard	10	13.34	Below-RZ
3	Hays Springs South	87	21.20	Above-RZ
4	Box Butte/Sioux County Line West	71	21.18	Through-RZ
5	Elmcreek-Miller	183	22.70	Below-RZ
6	Plymouth West	4	16.72	Above-RZ
7	Harrison South	29	20.66	Through-RZ
8	South of Silver Creek	39	14.13	Through-RZ
9	Fort Kearney Link	L50A	11.17	Through-RZ
10	Phillips & Giltner Spurs	34	0.40	Through-RZ
11	Swanton Spur	S76D	11.23	Above-RZ

Figure 5. Low traffic volume highways (numbers 1–11 on the map) selected for field investigation.

Statistical analyses of the field measurements were not performed because the amount of data was insufficient. Instead, a bar chart, illustrated in figure 6, was developed to simply present an overall view of field rut measurements with the average value and an error bar obtained from each gradation after a 3-year public service (from 2004 to 2007). Although not conclusive, one can expect from the figure that the RZ is not a factor that significantly governs the rutting performance of low traffic volume roadways, similar to that demonstrated in other studies for medium to high traffic volume pavements. Based on the field measurements along with the statistical analysis results and the experimental investigations, the gradations violating the Superpave RZ requirement (in other words, through-RZ mixture) performed similarly or sometimes better than the above-RZ or below-RZ mixtures. A more general and comprehensive conclusion can be derived with more data.

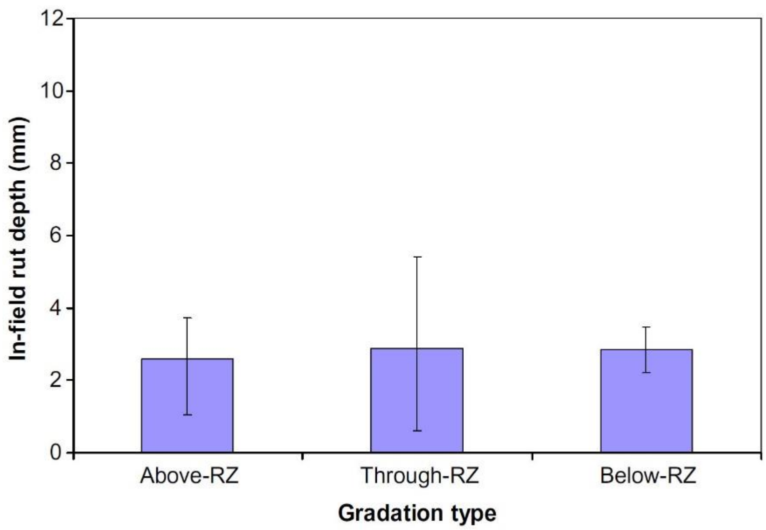

Figure 6. In-field rut measurements of each gradation type after 3-year public service.

5. Summary and conclusions

From the comparison and analysis in this study, the following summary and conclusions can be drawn:

- Statistical analyses of the APA rut data indicate that the gradation is a significant factor affecting the APA rut depth with a 90% significance level for the *SP-2* mix and a 99% significance level for the *SP-4 Special* mix. The below-RZ mixtures generally exhibited the highest rutting potential, and the above-RZ mixtures were the most rut resistant. However, there was no significant contrast observed between the below-RZ and the through-RZ mixtures, indicating that the mixtures violating Superpave RZ concept do not necessarily yield a higher rut potential in low traffic volume mixtures compared with the gradations in compliance with the RZ.
- Based on the experimental investigation through the APA performance test results and the densification curve analyses using the CDI-TDI concept, better rut resistance can be achieved from finer-graded mixtures. Coarser-graded mixtures such as the below-RZ and the second through-RZ mixtures were generally more susceptible to rutting. Therefore, the fineness of aggregate gradation rather than the RZ may be a factor affecting HMA rutting performance.
- Research findings obtained from this study generally agreed with other RZ-related studies, even though the target mixes for this study were low traffic volume local HMA mixtures that are typically designed with low quality aggregates (lower

CAA and FAA), while the other studies in the literature were mostly performed for medium to high traffic volume HMA mixes designed with high-quality materials.

- Analyses of in-field 3-year rut performance measurements for the *SP-4 Special* mix also agreed with the statistical analyses results and experimental observations in that the through-RZ mixture performed similarly or sometimes better than the mixtures that satisfy Superpave RZ concept.
- Even though some meaningful findings can be drawn from this study, the findings presented herein should be viewed with some cautions as they are based on only a single laboratory performance test, i.e., APA, with probably insufficient laboratory field data. Additional testing and/or more extensive analyses can confirm the conclusions derived from this study.

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